Naval Research Laboratory

Washington, DC 20375-5000

UNCLASSIFIED

NRL Report 9026

Superstructure Flow Distortion Corrections for Wind Speed and Direction Measurements Made from *Virginia* Class (CGN38-CGN41) Ships

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April 10, 1987

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): NRL Report 9026

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION: Naval Research Laboratory

6b. OFFICE SYMBOL (If applicable): Code 4110

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code): Washington, DC 20375-5000

7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: Naval Research Laboratory

8b. OFFICE SYMBOL (If applicable): Code 5750

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code): Washington, DC 20375-5000

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
64573N		X0954	DN091-023

11. TITLE (Include Security Classification): Superstructure Flow Distortion Corrections for Wind Speed and Direction Measurements Made from *Virginia* Class (CGN38-CGN41) Ships

12. PERSONAL AUTHOR(S): Blanc, Theodore V.

13a. TYPE OF REPORT: Final

13b. TIME COVERED: FROM ________ TO ________

14. DATE OF REPORT (Year, Month, Day): 1987 April 10

15. PAGE COUNT: 29

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): (See page ii)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: Theodore V. Blanc

22b. TELEPHONE (Include Area Code): (202) 767-2780

22c. OFFICE SYMBOL: Code 4110

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

★U.S. Government Printing Office: 1985—507-047

SECURITY CLASSIFICATION OF THIS PAGE

18. SUBJECT TERMS

Ship-induced errors of meteorological measurements
Correction of shipboard wind speed and direction measurements
Boundary-layer ship model wind tunnel tests
Errors in bulk method determined fluxes
Air-sea interaction

SECURITY CLASSIFICATION OF THIS PAGE

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SUPERSTRUCTURE FLOW DISTORTION CORRECTIONS FOR WIND SPEED AND DIRECTION MEASUREMENTS MADE FROM *VIRGINIA* CLASS (CGN38-CGN41) SHIPS

Abstract

The available literature describing the errors in wind measurements produced by the flow distribution around ships, masts, and towers is briefly reviewed. It is demonstrated that the wind speed and direction measurements made from the standard anemometer locations onboard a *Virginia* class ship are distorted by the wind blockage produced by the ship's superstructure, mast, and antennas. Even though the wind measurements are made near the top of the forwardmost mast, the wind speed error was found to be as large as 20% and the wind direction error as large as 5°. A correction scheme for determining the true wind speed and direction is presented.

INTRODUCTION

Ships by virtue of their sheer size and shape pose a massive obstruction to the wind. Although the hull of a ship is designed to move efficiently through water, little consideration is usually given to the ability of the above-water structure to move unobtrusively through the atmosphere. Wind speed and direction measurements of the ambient wind can be seriously distorted as air, deflected by the superstructure and masts, accelerates and deaccelerates around and over the ship to catch up with the surrounding atmosphere unaffected by the blockage. The typical accuracy of a well-designed shipboard wind sensor not exposed to flow distortion is $\pm 2\%$ for wind speed and $\pm 3°$ for wind direction. Blanc (1986a) has demonstrated that ambient wind speed measurements made even at standard anemometer locations atop forward masts can on some ships be in error by as much as 50%.

The direct implications of this problem to the day-to-day operations of a ship are obvious. Consider, for example, the importance in docking a large vessel under crosswind conditions or in the launch and recovery of helicopters from the deck. Wind speed and direction measurements are used by the ship to implement defensive procedures, to support navigation, to control weapon systems, and to prepare local oceanographic and atmospheric forecasts. Other implications are less obvious, but equally important. Blanc (1986b) has shown that ship-induced distortions can seriously affect the accuracy of the measurements needed for synoptic scale forecasting. The meteorological observations reported by ships are used by atmospheric and oceanic forecasting organizations, such as the National Weather Service and the U.S. Navy Fleet Numerical Oceanography Center, to make worldwide weather and sea

Manuscript approved February 4, 1987.

state forecasts. The quality of those forecasts can only be as good as the quality of the observations that go into them.

BACKGROUND

Augstein et al. (1974), in a comparison of data taken simultaneously from the deck of a ship and from a buoy, concluded that the ship's hull and superstructure induced sizable distortions in simple measurements of wind speed and other meteorological parameters. Hoeber (1977), in a specially designed experiment in which observations were taken simultaneously from the deck and from a forward boom, found that rudimentary shipboard measurements of ambient wind speed were very difficult. Kahma and Leppäranta (1981) determined that wind speed measurements made from one oceanographic research ship were in error by as much as 35% because of the flow distortion produced by its above-water structure. Elliott (1981) reports that ship model wind tunnel tests conducted by Thornton (1962) estimated the flow distortion error at some potential shipboard anemometer sites to be as large as 40%. Romanova and Samoylenko (1981) presented an interesting overview of the work done in the Soviet Union; they reported typical wind direction errors of $\pm 10°$.

Ching (1976), in a comparison of wind speed measurements made from a number of ship's masts and booms, found that the magnitude of the observed error was a function of the relative angle of approach of the wind to the ship. The least error occurred when the wind was aligned with the heading of the ship. Kidwell and Seguin (1978), in a comparison similar to Ching's, found with identical sensors on four ships that the sensors mounted on a forward boom did not necessarily yield more accurate measurements than those taken from a mast. Mollo-Christensen (1979) resolved these seeming conflicting results by wind tunnel tests; these tests demonstrated not only that the reference measurements must be made from a boom located upwind of the ship, but that the boom must be of a length equivalent to several times the windward cross section of the vessel (a length greater than it is frequently practical to construct from an engineering perspective). Bogorodskiy (1966) reported poor agreement between wind profile measurements taken from an 8-m boom forward of a ship and those taken from a buoy.

Wucknitz (1977), in a detailed study of the wind field distortions induced by an instrument support mast, found that even a narrow, single element, cylindrical mast could significantly alter wind speed measurements. Wucknitz concluded that, if sensors were mounted on opposite sides of a mast with a sensor distance to mast diameter ratio in excess of 15:1 and if the readings from the best exposed sensor were used, the measurement error could be kept to an acceptable level. The downwind effect of tower and mast structures on wind measurements has been studied by Moses and Daubek (1961), Gill et al. (1967), Cermak and Horn (1968), Dabberdt (1968a), and Camp and Kaufman

(1970). Upwind effects have been studied by Borovenko et al. (1963), Thornthwaite et al. (1965), Dabberdt (1968b), Izumi and Barad (1970), Angell and Bernstein (1976), Wucknitz (1980), Wieringa (1980), Dyer (1981), van der Vliet (1981), and Wessels (1984). They generally found the wind measurement error to be highly dependent on the wind direction, the distance and position of the sensor relative to the blockage, and the geometry of the flow obstruction.

Hoeber (1977) and Blanc (1986b) demonstrated that the distortion of meteorological measurements induced by ships can seriously affect the determinations needed for accurate weather and sea state forecasts. Blanc (1986b) proposed that the wind speed measurement error could be minimized by developing correction algorithms for the standard anemometer locations on each class of ship based on measurements made with ship models in a wind tunnel.

To properly simulate the wind field encountered by a structure the size of a ship, the model must be run in a boundary-layer simulation wind tunnel. Above an altitude of about 500 m, in a region known as the free atmosphere, the wind field moves as if the liquid and solid boundary of Earth were not present. Below 500 m, called the planetary boundary layer, the wind speed decreases with altitude because of the influence of friction produced by Earth's surface. Since the wind speed in the lower region generally decreases in an approximately logarithmic fashion, the magnitude of the wind encountered at various heights of the ship can differ significantly. The difference in wind speeds between 5 and 50 m above the ocean is typically in the order of 20% and is an important aspect of simulating the lower atmosphere. Unlike a conventional wind tunnel that generates a uniform wind speed profile, a boundary-layer tunnel produces a wind speed that decreases logarithmically with height. More information about boundary-layer wind tunnels may be found in Chapter 13 of Plate (1982).

METHODOLOGY

The *Virginia* class ship (CGN38-CGN41) is a nuclear-propelled, guided missile cruiser; four were commissioned between 1976 and 1980. An outline of the vessel is shown in Fig. 1. The ship is approximately 178 m long and 19 m wide; it is typically equipped with two anemometers (A in Fig. 1) mounted 41.3 m above the water. The sensors are attached midway out on a cross arm a distance of 6 m from either side of the forward-most mast. The mast is situated above and just aft of a large rotatable radar antenna array (B in Fig. 1). Both the mast and the radar antenna axes are located along the centerline of the symmetrically configured vessel. The ship has a helicopter landing pad (C in Fig. 1) located on the stern. More information may be found in Polmar (1981).

An approximately 3.7 m long 1:48 brass sheet metal scale model of the above-water portion of the USN *Virginia* (CGN38) was run in the atmospheric boundary-layer simulation wind tunnel operated by British Maritime Technology (BMT) in Teddington, England. (BMT was formally known as the

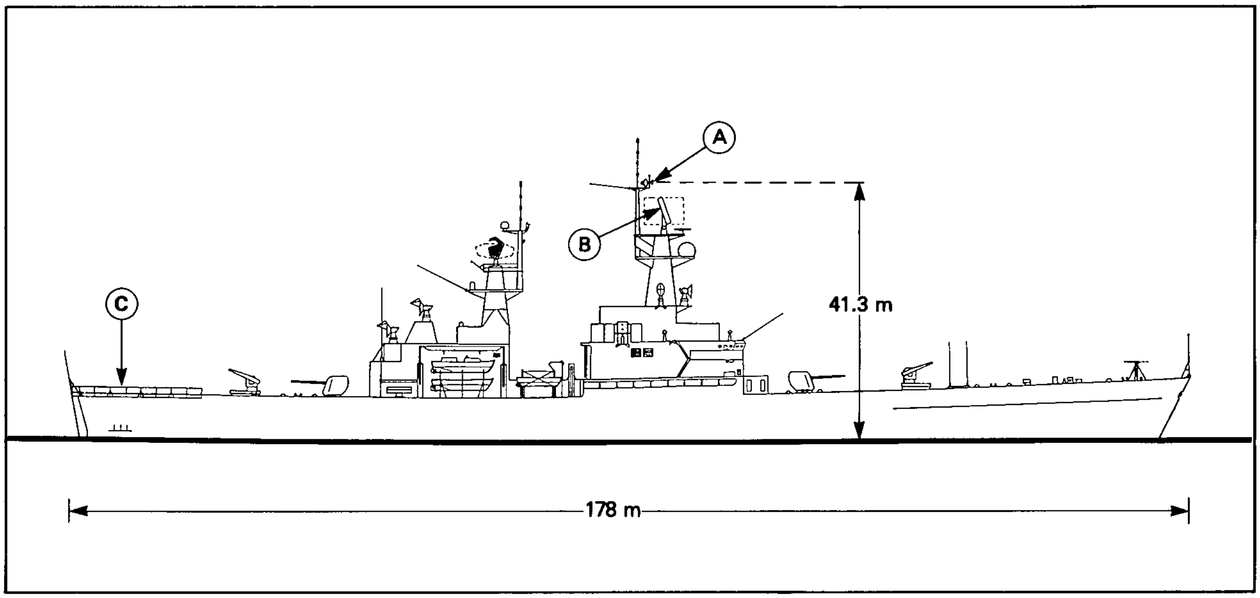


Fig. 1 — Side profile view of the 178 m long *Virginia* class (CGN38-CGN41) guided missle cruiser. Two anemometers (A) are located 41.3 m above the water 6 m on either side of a forward mast that is above and aft of a large rotatable radar antenna array (B). The 19 m wide ship has a helicopter landing pad (C) situated on the far aft deck.

National Maritime Institute located at the National Physical Laboratory.) Figures 2 and 3 show the model inside the tunnel. The appropriate vertical wind profile in the BMT tunnel is achieved by employing on the floor a series of upwind air jets that oppose the main tunnel flow. The jets are visible in the upper right-hand corner of Fig. 2. The approach is based on a technique developed by Nagib et al. (1976). The overall usable test area in the tunnel is 4.8 m wide, 15 m long, and 2.4 m high.

A small two-dimensional sensor, consisting of two hot wires approximately 0.005 mm in diameter and 1.25 mm long placed at right angles to each other, was used to obtain the wind velocity measurements. The sensor simultaneously measures the wind speed parallel and transverse to the mean tunnel flow and thus enables the determination of the horizontal wind speed and direction. The vertical wind speed component was not measured at this time because the propeller vane-mounted anemometers usually used on ships are relatively insensitive to the vertical wind component. More information about hot-wire and propeller anemometers is given in Chapter 1 of Dobson et al. (1980).

Without the ship model present, the hot-wire sensor was placed in the tunnel and centered above the model turntable. The sensor was moved vertically by a remote-controlled carriage device, and a profile measurement was taken to ensure that the wind decreased in a manner appropriate for simulating the atmospheric boundary layer over the ocean. The sensor carriage device is visible in the upper portion of Fig. 3. Each measurement was averaged over a period of 20 s. Figure 4 shows the measured logarithmic profile in the wind tunnel.

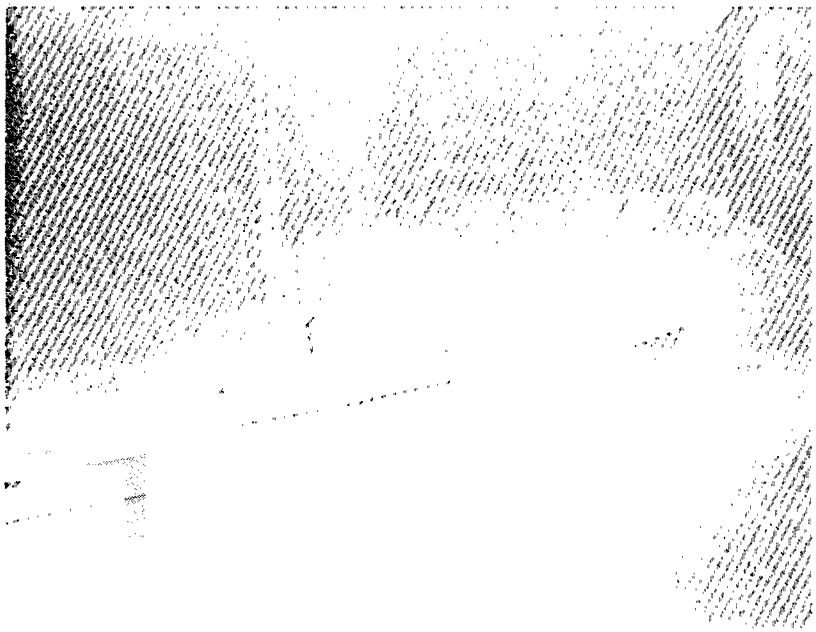
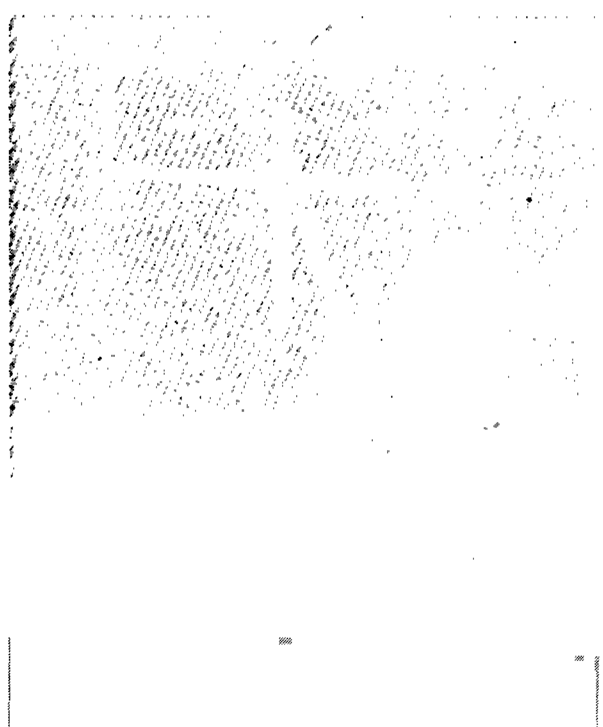


Fig. 2 — Scale model of the USN *Virginia* (CGN38) in the BMT boundary-layer wind tunnel as viewed looking into the wind. The 3.7 m long model is shown with the wind coming from 315° over the port side. Note the counterjets on the floor upwind of the model. John Wills of the BMT Environmental Flow Group is shown in the background to illustrate the size of the tunnel's working area.



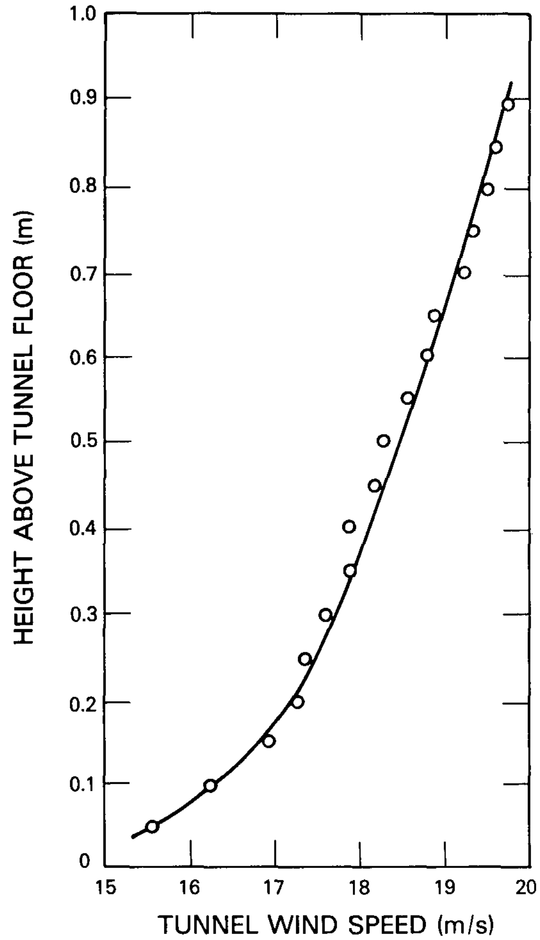


Fig. 4 — The logarithmic wind profile generated in the empty BMT boundary-layer wind tunnel for the *Virginia* class tests. Each measurement was averaged over a period of 20 s.

The sensor height was set to 0.86 m (equivalent to the *Virginia* class standard anemometer altitude of 41.3 m above mean water), the tunnel speed was maintained at 19.8 m/s (38.5 knots), and the wind speed was observed by use of a standard reference pitot tube wind speed sensor located upwind near the ceiling. When a ship model is placed in the tunnel or the model is rotated and changes the wind blockage, it tends to slightly alter the mean wind speed of the tunnel. The pitot tube readings were used to control the tunnel speed and to ensure that the tunnel conditions were kept constant throughout the test.

The model was then placed in the tunnel and centered on the turntable so that the model could be rotated about the vertical axis of one of the two standard anemometer locations to simulate a shipboard vane-mounted anemometer rotated into the wind. This arrangement can be seen in Fig. 5. Note the symmetrical configuration of the ship's superstructure, the forward mast arrangement with the two anemometer locations (A and B in Fig. 5), and the large forward rotatable radar antenna array (C in Fig. 5).

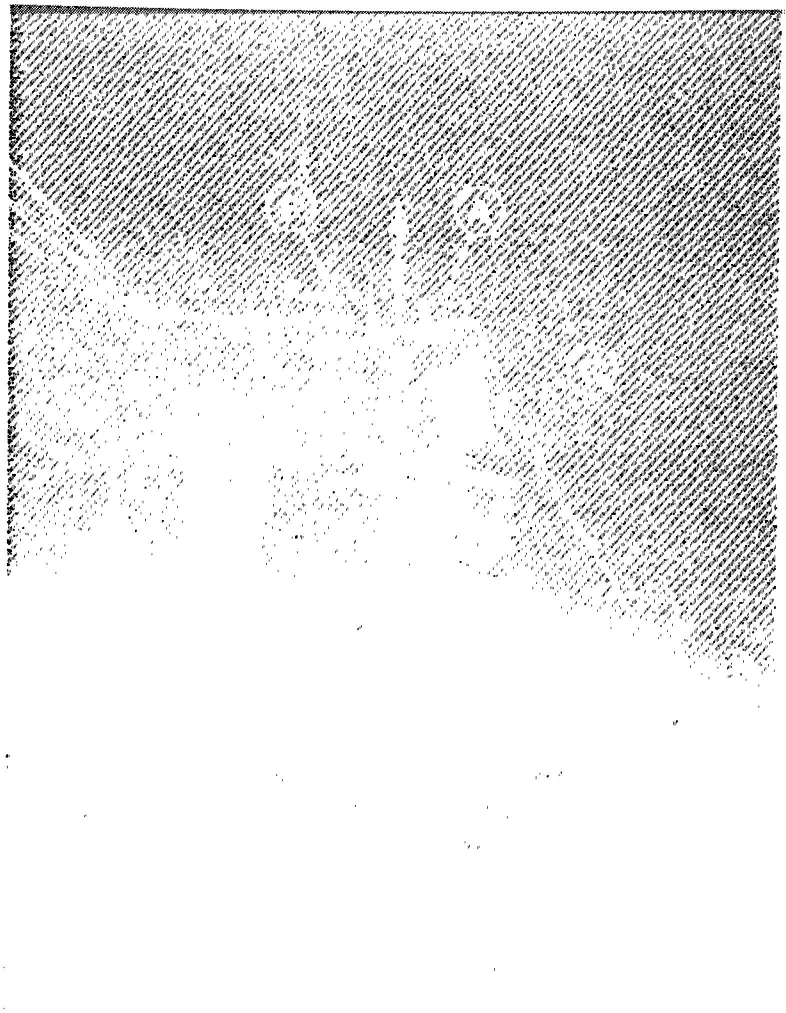


Fig. 5 — Close-up view of the ship model with the two-dimensional wind sensor centered over the model turn table at the starboard anemometer location. The model is shown with the wind coming from 315° over the port side from the right-hand side of the figure. Both the port (A) and starboard (B) anemometer locations are situated equidistant from the forward mast on the centerline of the vessel. The large rotatable radar antenna array (C) is forward of the mast. Its axis of rotation is also located on the ship's centerline. Test results were obtained with the antenna facing toward the ship's bow.

Because the radar antenna array was located so close to the anemometers, we were concerned with the influence that the antenna's orientation would have on our tests. Although the antenna's axis of rotation is located on the centerline of the ship, the antenna array itself is asymmetric in shape, extending further to the port side when the array is facing forward. To test the influence of the antenna's orientation, we positioned the model in the tunnel to produce what we considered to be the worst case situation. With the wind coming over the port side at an angle of 315° relative to the ship, we took measurements at both the port and starboard anemometer locations with the antenna facing into the wind, the antenna 45° clockwise and counterclockwise to the wind, and the antenna 90° to the wind. The different orientations of the antenna were found to produce a variation of about 2% in wind speed readings—the same magnitude of reproducibility the wind tunnel results would have if the antenna were set at a fixed orientation. For the remainder of the tests, we set the antenna so it faced toward the ship's bow. See Figs. 3 and 5.

Measurements from different wind directions were simulated by rotating the model in 15° increments. The wind direction, relative to the ship, was recorded by use of the coordinate system described in Fig. 6, in which 0° indicated a wind coming over the bow, 90° indicated a wind over the starboard, 180° indicated a wind over the stern, and 270° indicated a wind over the port. The same procedure was then repeated for the remaining anemometer location. Wills and Cole (1985) give more details about the wind tunnel measurements.

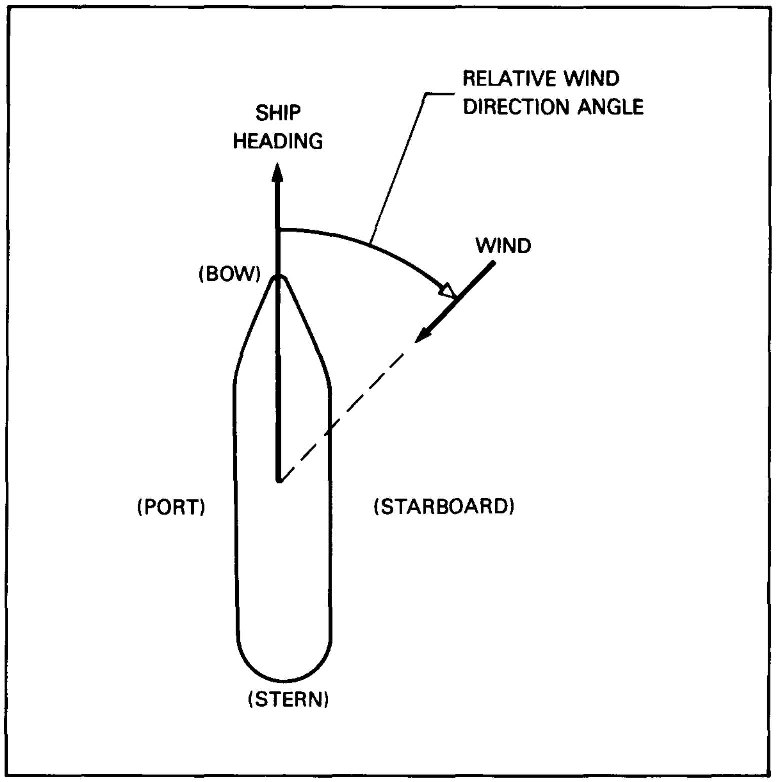


Fig. 6 — Overhead view of the relative shipboard wind direction coordinate system used in this report

RESULTS AND DISCUSSION

The measurements taken with the model in the tunnel were compared with those taken at the same altitude without the model present. Because the tunnel conditions were kept constant and the ship-induced changes were calculated in terms of relative percent or direction, the results are independent of the wind speed employed in the tunnel or the wind speed that would be encountered by the real ship stationary in the water. The results showing the measurement distortions produced by the entire above-water portion of the ship (hull, above-deck structure, masts, antennas, etc.) are shown in Figs. 7

through 10 as a function of wind direction. Because of the symmetrical configuration of the vessel's superstructure and anemometer locations about the ship's centerline, Figs. 7 and 9 appear as nearly exact right-to-left transposed images of each other, and Figs. 8 and 10 appear as an inverted right-to-left transposition. In other words, the distortion observed at the port anemometer location when the wind is coming from 315° relative to the ship is virtually identical to the distortion observed at the starboard anemometer location when the wind is coming from 45° relative to the ship.

Wills and Cole (1986) have estimated the uncertainty (reproducibility) of the wind tunnel results used in this report to be ±2% for the wind speed error and ±2° for the wind direction error. If one were to transpose the results of Figs. 7 and 9 and Figs. 8 and 10 as described above, the variation would substantiate this estimate.

The vertical wind profile of the lower atmosphere is known to change from the ideal logarithmic form as a function of atmospheric stability. The stability of the atmosphere is a measure of its thermal-to-mechanical turbulent energy balance and is frequently expressed in terms of a characteristic turbulence scale size known as the Monin-Obukhov length. Under unstable conditions atmospheric turbulence is enhanced, and under stable conditions it is suppressed. More information may be found in Blanc (1986b). Over the ocean the stability typically ranges from an unstable size of −10 m to a stable size of +100 m. For our work we have assumed the most general condition, a neutral stability of zero in which the thermal and mechanical energy components are balanced. This is typical of an atmosphere that is well mixed by winds of 20 knots or more. More information about the wind profile stability dependence may be found in Chapter 7 of Sutton (1953).

Under neutral stability conditions, a wind profile can be represented as a straight line when plotted on a semilogarithmic graph in which altitude is represented on a vertical logarithmic scale and wind speed is represented on the linear horizontal abscissa. See for example Fig. 11. If the decrease in wind speed is projected downward in altitude to the virtual origin where the speed would be zero, this yields a measure of the surface roughness height known as the roughness length. However, the physical meaning of the projected wind profile should not be taken too literally. For more information see Krügermeyer et al. (1978). It is generally accepted that the roughness or choppiness of the ocean tends to increase with increased wind speed, slightly decreasing the slope of the logarithmic profile. Over the ocean the roughness length typically ranges from approximately a smooth 1×10^{-4} to a rough 1×10^{-3} m. The logarithmic wind profile used for this study, Fig. 4, if scaled to the height of the model, is that which would be produced by an ocean roughness equivalent to about 2×10^{-4} m, a typical value encountered in the real world. More information about the wind profile roughness dependence is given in Chapter 9 of McIntosh and Thom (1973).

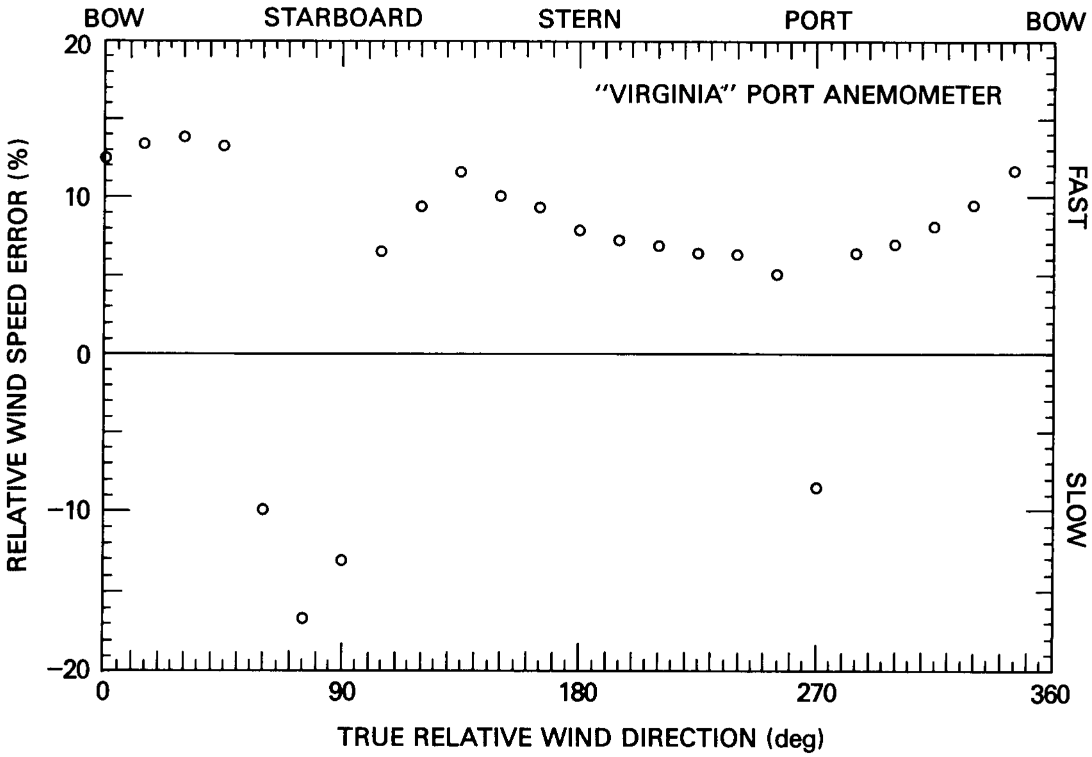


Fig. 7 — Wind tunnel results showing the wind speed measurement error for the port anemometer location owing to wind blockage for a *Virginia* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind speed error is ±2%.

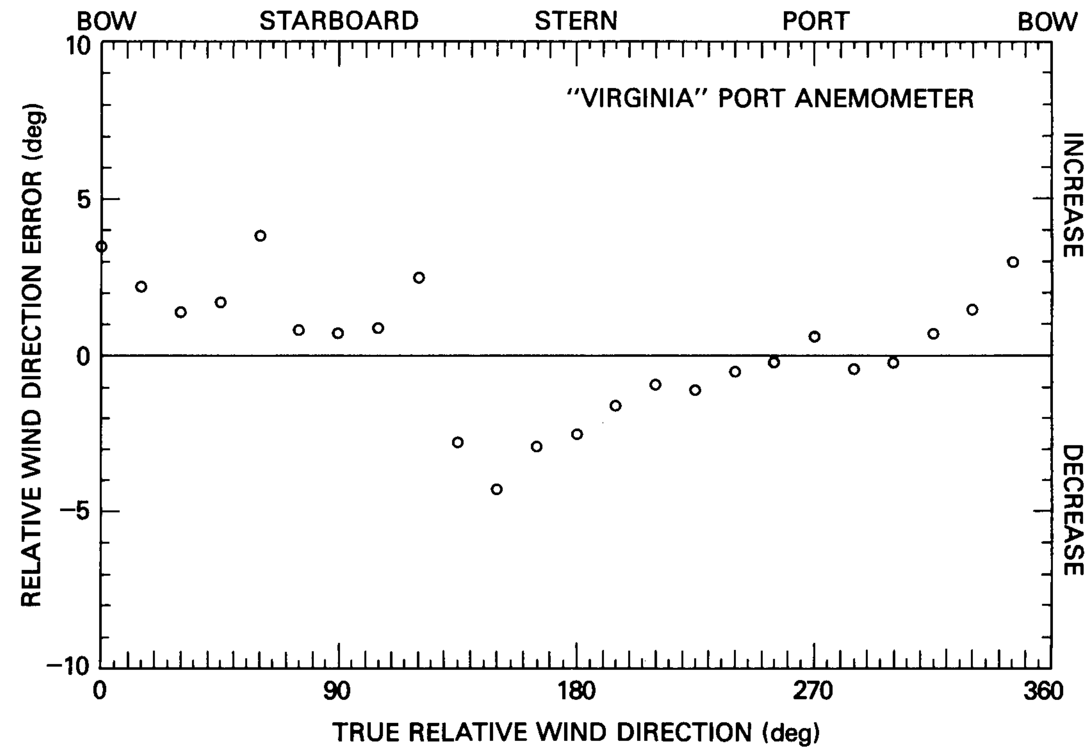


Fig. 8 — Wind tunnel results showing the wind direction measurement error for the port anemometer location owing to wind blockage for a *Virginia* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind direction error is ±2°.

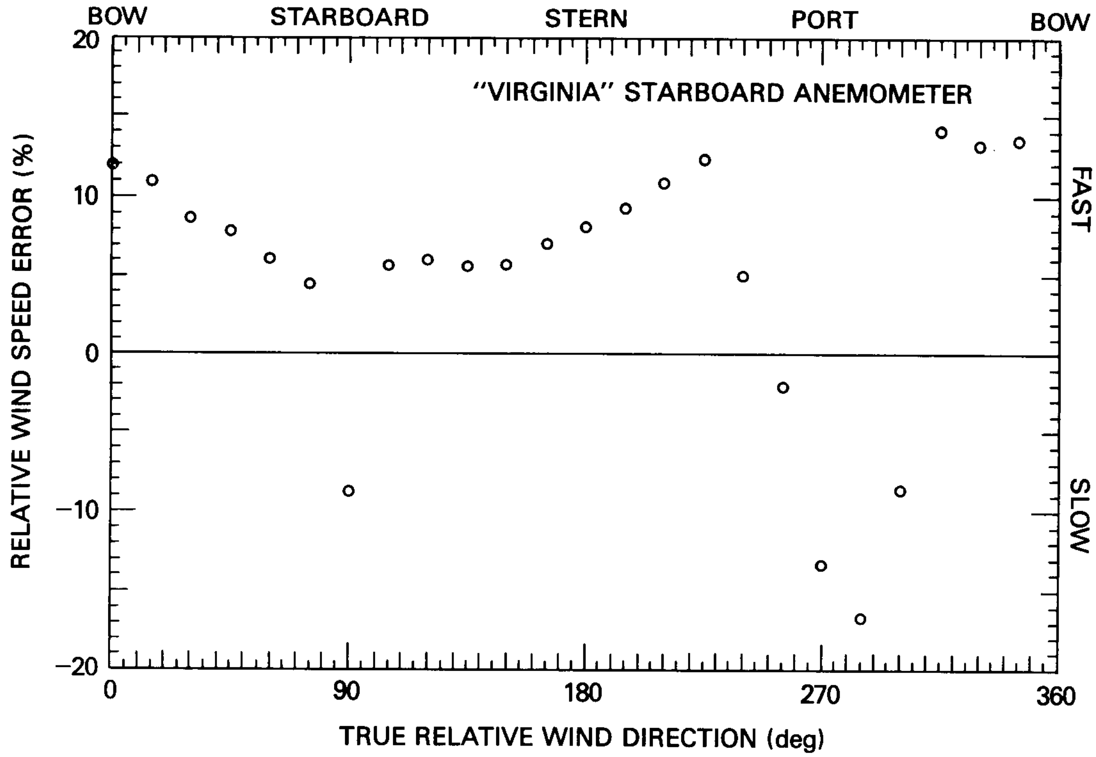


Fig. 9 — Wind tunnel results showing the wind speed measurement error for the starboard anemometer location owing to wind blockage for a *Virginia* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind speed error is ±2%.

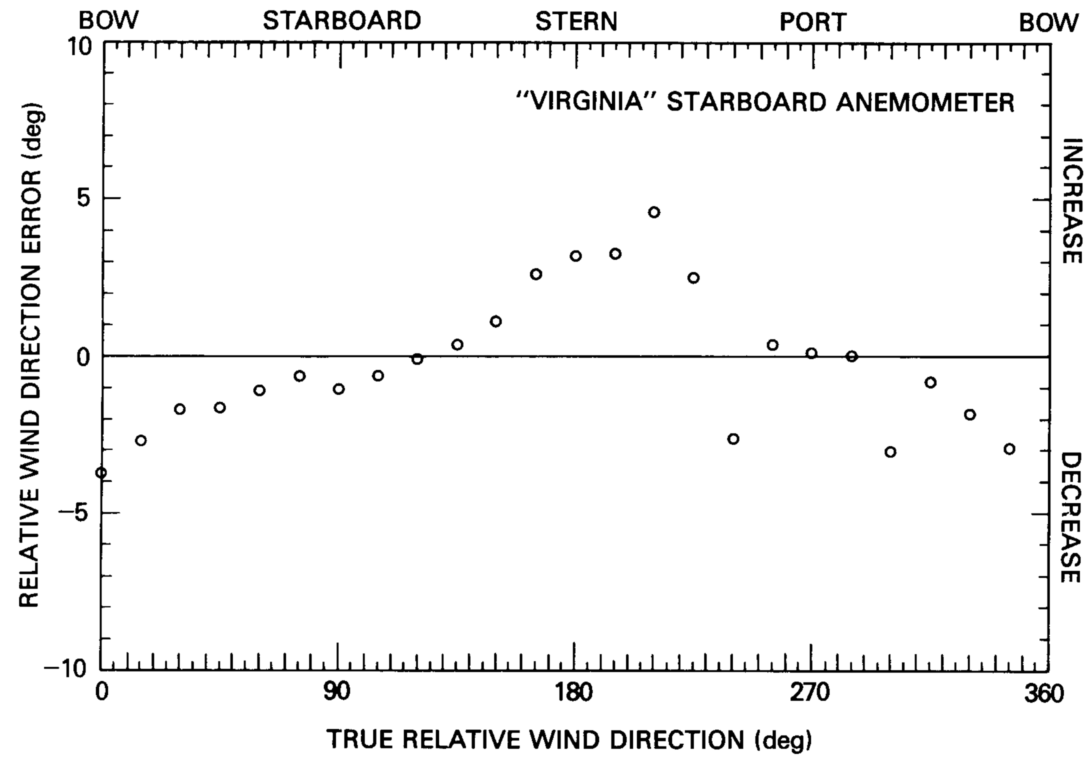


Fig. 10 — Wind tunnel results showing the wind direction measurement error for the starboard anemometer location owing to wind blockage for a *Virginia* class ship as a function of the true wind direction relative to the ship. The estimated uncertainty of the wind direction error is ±2°.

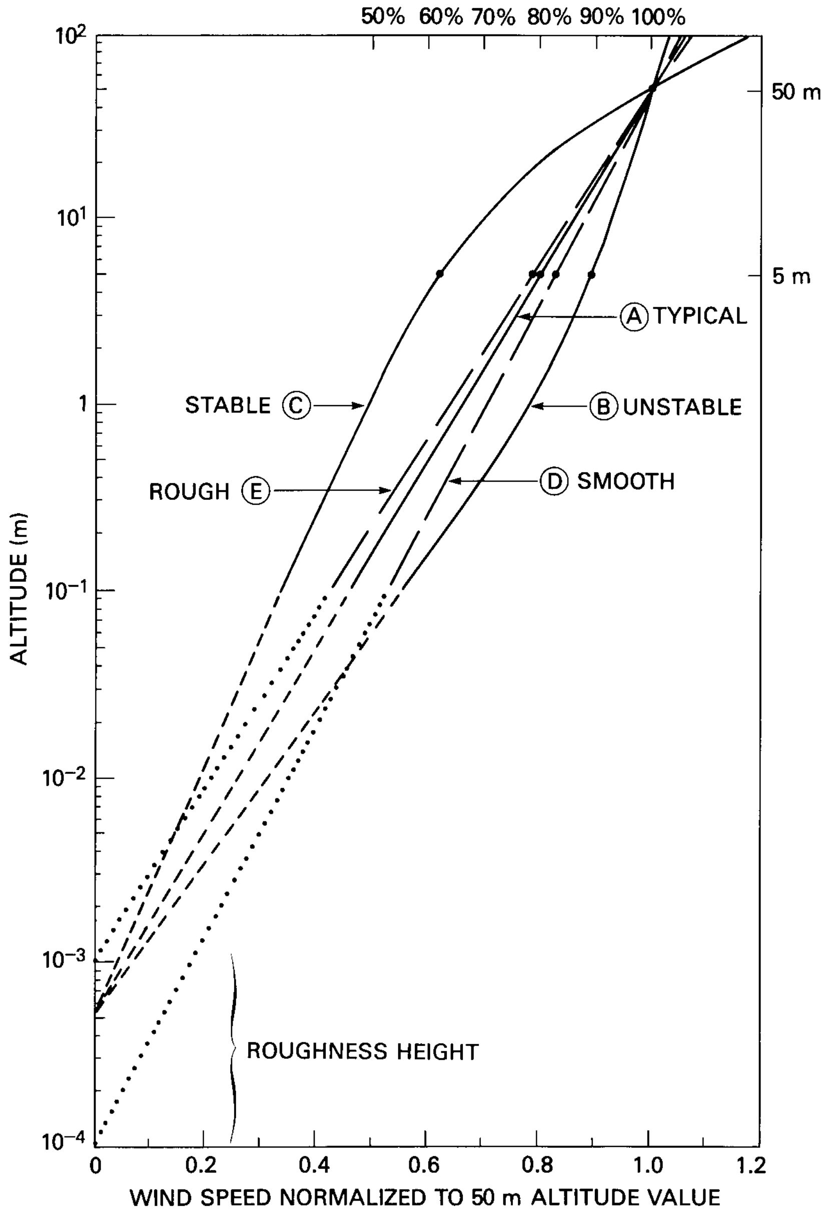


Fig. 11 — An example of the variations in a wind profile shown normalized to the 50 m altitude wind speed for three stability conditions: typical (A) neutral, (B) unstable, and (C) stable for a given roughness of 5×10^{-4} m and variations in a wind profile for two roughness conditions: a smooth (D) 1×10^{-4} m, and a rough (E) 1×10^{-3} m for a given typical neutral stability.

If we were to define a typical case as one in which the stability was a neutral zero and the ocean surface roughness a middle range value of 5×10^{-4} m, the 5 m altitude wind speed would be 80% of the 50 m value (curve A in Fig. 11). In other words, if the wind speed at an altitude of 50 m were 10 knots, the wind speed at 5 m would be 8 knots. If the stability were varied from an unstable -10 m (curve B in Fig. 11) to a stable $+100$ m (curve C in Fig. 11) and the roughness kept at 5×10^{-4} m, the 5 m altitude wind speed would range from 89 to 62% of the 50 m value—a mean variation of about ± 17 parts per hundred from our typical case. If the surface roughness were varied from a smooth $1 \times$

10^{-4} m (curve D in Fig. 11) to a rough 1×10^{-3} m (curve E in Fig. 11) and the stability kept neutral, the 5 m altitude wind speed would range from 82 to 79% of the 50 m value—a mean variation of about ±2 parts per hundred from our typical case. Note that in all cases the wind speed decreases with decreasing altitude. It is estimated that a variation of 10 parts per hundred in the 50 to 5 m wind profile would result in a variation of about 1% in the wind speed error values presented in Figs. 7 and 9 for the standard anemometer locations.

Note that we have not considered the alteration in wind blockage produced by sea-state-induced change of ship attitude (pitch and roll), the influence of a helicopter parked on the ship's aft deck, the presence of auxiliary boats on the side decks, or the orientation of the large forward antenna array. Further, we have not considered the influence that the ship's velocity would have on the wind profile encountered by the ship. If a ship were under way through a still atmosphere, the self-generated wind encountered by the ship would be constant with altitude. When the self-generated uniform ship velocity profile is combined with the logarithmic varying velocity profile of the atmosphere, the situation becomes more complex. Consider, for example, a simple case in which the ship is moving north at 20 knots and our typical atmosphere is moving west at 10 knots at 50 m altitude. The combined velocity at 50 m is 22.4 knots at 27°. The combined velocity at 5 m is 21.5 knots at 22°. Not only is the vertical wind speed differential different from our typical case—a variation of 20 parts per hundred—but the wind directions encountered by the ship at the two altitudes differ by 5°.

In the future it may be possible to modify a correction scheme to take into consideration the atmospheric stability, sea surface roughness, pitch and roll attitude, and the velocity of the ship. For example, the stability can be estimated by the temperature differential observed between the air and sea. Further studies will be required to determine if such modifications would improve the accuracy of a flow distortion correction scheme. The present results suggest, however, that such modifications would not significantly improve a correction scheme for the *Virginia* class ships.

CONCLUSIONS

The potential accuracy of a properly exposed shipboard wind sensor is about ±2% for wind speed and ±3° for wind direction. We have studied the simplest environmental case possible, one in which the atmospheric stability is neutral, the sea surface roughness is constant, the pitch and roll attitude is zero, and the ship is dead in the water. The wind tunnel results presented in this report demonstrate that the wind speed and direction measurements made at the standard anemometer locations onboard a *Virginia* class ship are in error because of the wind blockage produced by the ship's superstructure, mast, and antennas. The measurements made near the top of the forwardmost mast were found to be in error by as much as 20% for the wind speed and 5° for wind direction. To obtain undistorted shipboard readings appropriate to the accuracy of the wind sensor, a correction scheme specifically tailored to the ship class and anemometer location must be employed because wind flow distortions are highly dependent on the wind direction, sensor location, and the structural configuration of the vessel.

The wind tunnel observations shown in Figs. 7 through 10 were made referenced to the true wind direction relative to the ship. However, on a ship it is not possible to measure the true wind direction, only the distorted observed direction. To make the results usable for determining the undistorted wind speed and direction, we converted the flow distortion error results into correction values and computed the observed direction by use of the true direction and error information by linear interpolation. In other words, we solved the following equations in reverse to obtain the observed values and then interpolated. Because the typical fluctuation in wind direction observed over the ocean while averaging a reading is about $\pm 5°$, the interpolation was done at 5° intervals. The correction values are presented in Figs. 12 through 15 and in Tables 1 and 2. The results could be easily adapted to an automated system that could compute and display the corrected readings on the ship's bridge or wherever the information might be needed. For a given observed wind direction relative to the ship,

$$\text{(True Wind Speed)} = \text{(Observed Wind Speed)} \times \text{(Wind Speed Correction)}$$

and

$$\text{(True Wind Direction)} = \text{(Observed Wind Direction)} + \text{(Wind Direction Correction)}.$$

The typical overall accuracy of the corrected values under a variety of ship velocity and atmospheric conditions, exclusive of any excessive sensor calibration error, is estimated to be $\pm 5\%$ for wind speed and $\pm 5°$ for wind direction.

For example, if the average relative wind speed and direction observed by a correctly calibrated port anemometer is 12.0 knots at 10°, it can be calculated from Table 1 that the true relative wind speed is 10.7 knots (± 0.5 knots) and the true relative wind direction is 7° ($\pm 5°$) for the altitude of 41.3 m.

Note that in those cases for which there is little or no correction, such as for the port anemometer wind speed measurement at 260° in Fig. 12, this does not mean that it is a region of no distortion, but rather one in which two or more opposing distortions have tended to balance themselves out.

In the future we hope to study other classes of ships and to develop for each class a scheme so that for a given relative wind direction and speed observed at the standard anemometer locations it will be possible to estimate the wind speed, direction, and superstructure-induced turbulence at various locations over the flight deck and in the wind shadow for the vessel.

The figures and tables presented in this report are all referenced relative to the ship. To determine the meteorological wind speed and direction of the atmosphere, it is necessary to remove the ship's speed and heading from the results.

NOTE

Figs. 12 through 15 are on pages 16 and 17.

Table 1 is on pages 18 and 19.

Table 2 is on pages 20 and 21.

ACKNOWLEDGMENTS

The author is indebted to John Wills and Laurie Cole of British Maritime Technology for conducting the wind tunnel tests under contract N00014-85-C-2341 for the Naval Research Laboratory. Their assistance and cooperation has made this endeavor possible. This report has profited by the helpful comments made by Fred Dobson of the Bedford Institute of Oceanography (Canada) and by Peter K. Taylor of the Institute of Oceanographic Sciences (United Kingdom). This work was funded by the Anti-Ship Missile Defense System Program of the United States Navy.

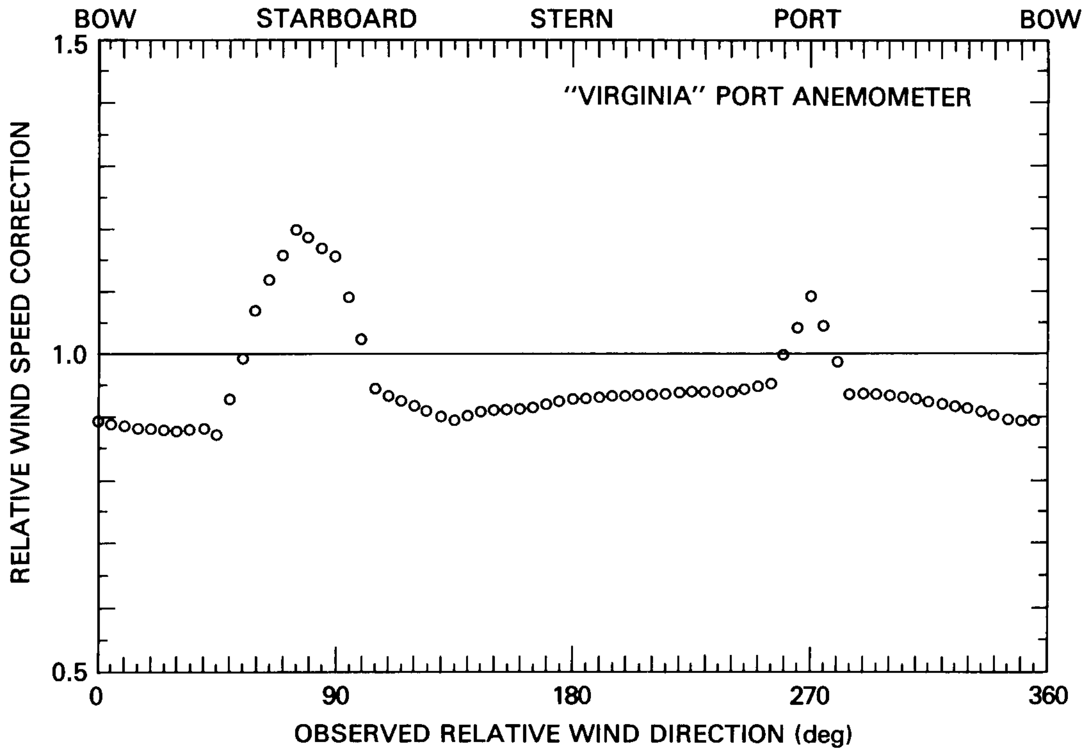


Fig. 12 — Wind speed flow distortion correction for the standard port anemometer location onboard the *Virginia* class ship as a function of the observed wind direction relative to the ship

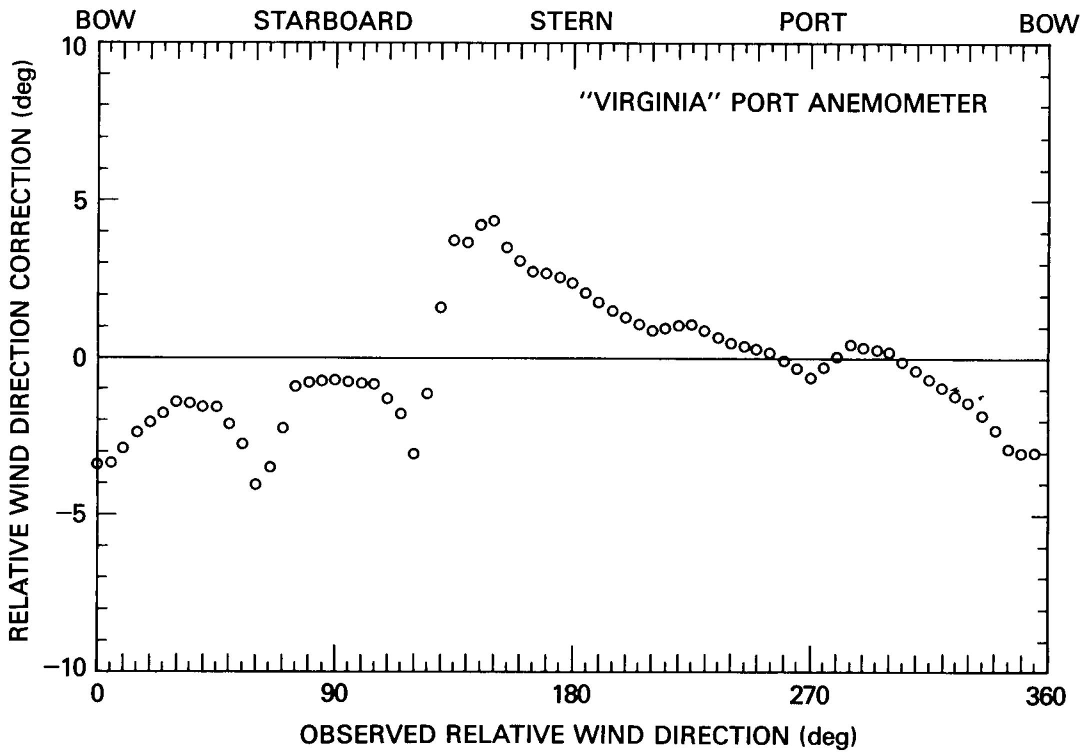


Fig. 13 — Wind direction flow distortion correction for the standard port anemometer location onboard the *Virginia* class ship as a function of the observed wind direction relative to the ship

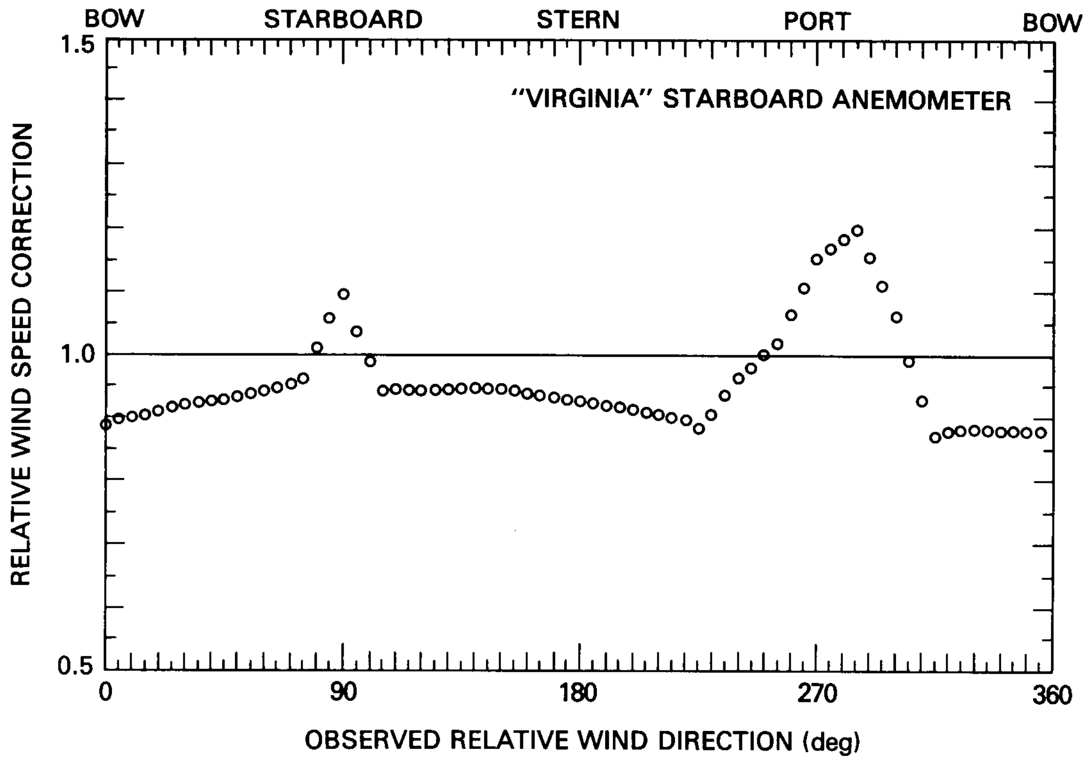


Fig. 14 — Wind speed flow distortion corrections for the standard starboard anemometer location onboard the *Virginia* class ship as a function of the observed wind direction relative to the ship

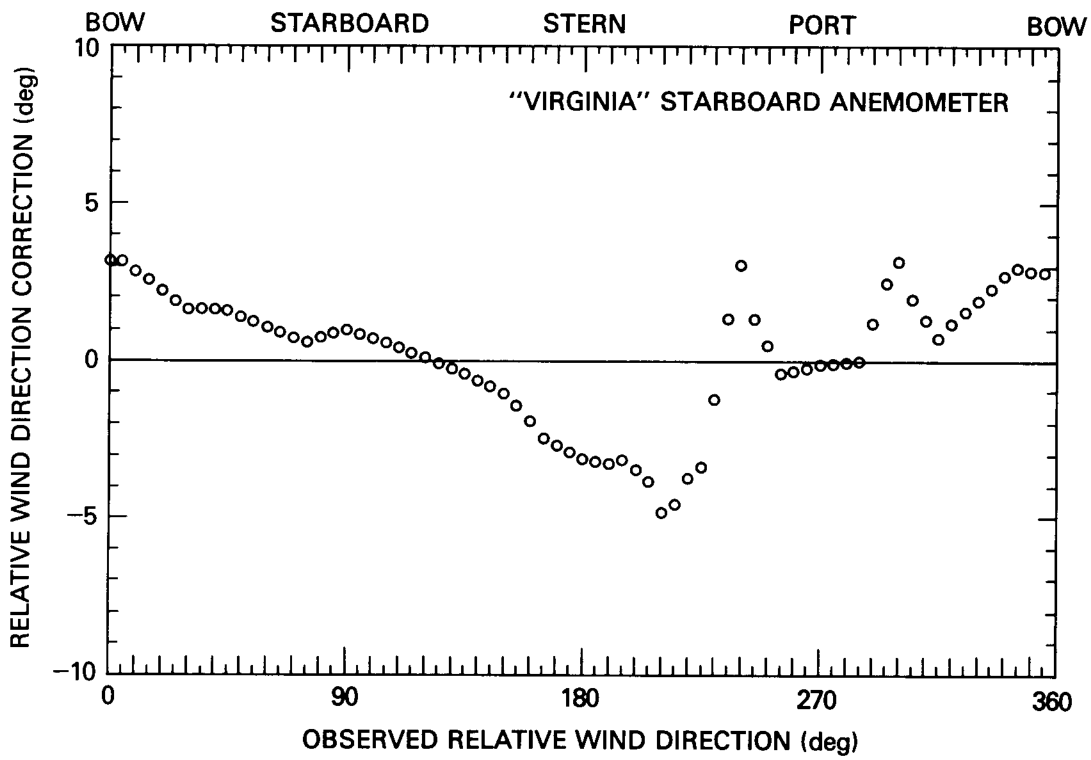


Fig. 15 — Wind direction flow distortion correction for the standard starboard anemometer location onboard the *Virginia* class ship as a function of the observed wind direction relative to the ship

Table 1 — Flow Distortion Corrections for the Standard Port Anemometer Location Onboard the *Virginia* Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
0	.89	−3
5	.89	−3
10	.89	−3
15	.88	−2
20	.88	−2
25	.88	−2
30	.88	−1
35	.88	−1
40	.88	−2
45	.87	−2
50	.93	−2
55	.99	−3
60	1.07	−4
65	1.12	−4
70	1.16	−2
75	1.20	−1
80	1.19	−1
85	1.17	−1
90	1.16	−1
95	1.09	−1
100	1.02	−1
105	.95	−1
110	.93	−1
115	.93	−2
120	.92	−3
125	.91	−1
130	.90	2
135	.89	4
140	.90	4
145	.91	4
150	.91	4
155	.91	4
160	.91	3
165	.92	3
170	.92	3
175	.93	3

Table continued on next page.

Table 1 (Cont.) — Flow Distortion Corrections for the Standard Port Anemometer Location Onboard the *Virginia* Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
180	.93	2
185	.93	2
190	.93	2
195	.93	2
200	.93	1
205	.93	1
210	.94	1
215	.94	1
220	.94	1
225	.94	1
230	.94	1
235	.94	1
240	.94	0
245	.94	0
250	.95	0
255	.95	0
260	1.00	0
265	1.04	0
270	1.09	−1
275	1.05	0
280	.99	0
285	.94	0
290	.94	0
295	.94	0
300	.94	0
305	.93	0
310	.93	0
315	.93	−1
320	.92	−1
325	.92	−1
330	.92	−1
335	.91	−2
340	.90	−2
345	.90	−3
350	.90	−3
355	.90	−3

Table 2 — Flow Distortion Corrections for the Standard Starboard Anemometer Location Onboard the *Virginia* Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
0	.89	3
5	.90	3
10	.90	3
15	.90	3
20	.91	2
25	.92	2
30	.92	2
35	.92	2
40	.93	2
45	.93	2
50	.93	1
55	.94	1
60	.94	1
65	.95	1
70	.95	1
75	.96	1
80	1.01	1
85	1.06	1
90	1.10	1
95	1.04	1
100	.99	1
105	.94	1
110	.95	0
115	.94	0
120	.94	0
125	.94	0
130	.95	0
135	.95	0
140	.95	−1
145	.95	−1
150	.95	−1
155	.94	−1
160	.94	−2
165	.94	−2
170	.93	−3
175	.93	−3

Table continued on next page.

Table 2 (Cont.) — Flow Distortion Corrections for the Standard Starboard Anemometer Location Onboard the *Virginia* Class Ship

Observed Relative Wind Direction (deg)	Relative Wind Speed Correction	Relative Wind Direction Correction (deg)
180	.93	−3
185	.92	−3
190	.92	−3
195	.92	−3
200	.91	−3
205	.91	−4
210	.91	−5
215	.90	−5
220	.90	−4
225	.88	−3
230	.91	−1
235	.94	1
240	.96	3
245	.98	1
250	1.00	1
255	1.02	0
260	1.06	0
265	1.11	0
270	1.15	0
275	1.17	0
280	1.18	0
285	1.20	0
290	1.16	1
295	1.11	3
300	1.06	3
305	.99	2
310	.93	1
315	.87	1
320	.88	1
325	.88	2
330	.88	2
335	.88	2
340	.88	3
345	.88	3
350	.88	3
355	.88	3

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